1947-09

A light-weight multi-channel telemetering system

Forter, Samuel Alexander

Cambridge, Massachusetts; Massachusetts Institute of Technology

7.l 185 - 1952

A LIGHT-WEIGHT MULTI-CHANNEL

TELEMETERING SYSTEM

by

Samuel Elexander Forter
Lieutenant Commander, U. S. Navy

B. S. in E. E.
from the

United States Naval Academy

June, 1940

Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Science

from the

Massachusetts Institute of Technology
Department of Electrical Engineering

September, 1947

Signature of Author Sam A Forter

Instructor in Charge
of Research ______________________

Chairman of Departmental
Committee on Graduate
Students ______________________

ABSTRACT

Current telemetering systems are too heavy and offer too few channels for successful application to the investigation of supersonic test vehicles. A study of the available systems indicates three factors which are uniformly inefficient. These factors are (1) the duplication of circuitry incident to the use of a separate amplifier for each channel; (2) inefficient methods of electronic commutation; (3) waste of power by the continuous excitation of measuring bridges.

A system is proposed which obviates these three points of inefficiency. A single amplifier for the whole system and a commutation scheme using a binary scaling circuit and a resistance matrix reduce the tube requirements for these two functions from 480 tubes to 45. Power is conserved by exciting the measuring bridges only during the time that information is desired from them. This process reduces the power requirements for bridge excitation from the power required for continuous excitation by a factor equal to the reciprocal of the number of channels.

Following these principles, circuits were constructed which indicate that the proposed system seems entirely practical. Such a system should be lighter than any of the present ones and also capable of providing at least four times as many channels.

TABLE OF CONTENTS

I would like to thank Professor W. H. Radford for his constructive supervision of this thesis.

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

Telemetering is the process of measuring a value in one place and obtaining the result of the measurement in another place. Light weight systems were developed first for upper air soundings for meteorological purposes, and since their development the emphasis on light weight in telemetering systems has been almost entirely in the fields of upper air sounding and flight testing of aircraft.

The first meteorological radiosondes were introduced in 1929 by Bureau[1] and Moltchanoff[2] of France and Russia respectively. Both these systems provided only two channels, one for temperature and one for pressure. Later systems provided three channels,[3] the third for humidity indications. Meteorological sondes were satisfactorily light - about two pounds - but their specialized measuring devices prevented their general application to other tele-

1. R. Bureau, "Sondages de Pression et de Temperature par Radiotelegraphie," Comptes Rendues, June 1929, V. 188, p. 1565.

2. Anon. Uber Radiosonde-Konstruktionen, Internationalen Meteorologischen Organization, March 1937, Berlin.

3. E. Duckert, "Radiosonde Telefunken," Beitrage zur Physik der Freien Atmosphare, 1933, V. 20, p. 303.

metering problems.

Telemetering for aircraft during test flights was first used in 1940. The original systems did no more than indicate on the ground the readings of dial type instruments in the aircraft.[1] This means of telemetering was not satisfactory since most of the measurements desired from an aircraft in test flight were most easily provided by a means which did not directly produce a dial type indication. The first system that provided intelligence for transmission to the ground without first converting to a dial indication was the Vultee Radio Recorder.[2] This system directly used the output of strain-gauge or other a.c. bridges to modulate the transmitted signal and indicate observed values in the aircraft.

A successful example of the telemetering systems developed for flight testing conventional aircraft is N. D. R. C. Telemetering System, Type 1, Model B.[3] This system weighs about 135 pounds and provides information from 18 different sources at a sampling rate of 1000 samples per

1. O. S. R. D. Report, No. 1459, "Wurlitzer System for Telemetering Slow-Varying Flight Instruments."

2. H. D. Giffen, "Vultee Radio Recorder," Aeronautical Engineering Review, July 1943, V. 2, no. 7, p. 9.

3. Instruction Book, NDRC Telemetering System, Type 1, Model B, Raymond Rosen and Company, Philadelphia, Manufacturers.

channel per second. Even though the weight of this system seems excessive in comparison with the weight of meteorological sondes, it must be realized that the system still weighs no more than a small man and can provide more information at a faster rate than any human. These two factors make a telemetering system worthwhile for conventional aircraft.

For a more detailed history of light weight telemetering, a seminar entitled "The Development of Airborne Telemetering" by S. A. Porter is available in the Vail Library.

CHAPTER II

THE PROBLEM

The introduction of jet and rocket propulsion and the consequent desire for supersonic aircraft and guided missiles has caused great emphasis to be placed on decreasing the weight of telemetering systems and increasing the number of channels.

Light weight is important in order that the size of the test vehicles will not have to be increased simply to carry the telemetering system. Small test vehicles are desirable from a standpoint of economy. Test vehicles in themselves are necessary for two primary reasons. First, they must be used to gather data concerning the transonic speed region. Up to the present time it has been impossible to construct a wind tunnel for use at these speeds because of the violent turbulence. This factor requires the use of test vehicles in actual flight. Next, before the data obtained from supersonic wind tunnels can be adequately exploited, this data and data obtained from actual flights must be correlated.

A large number of channels is desirable in order that data from identical flight conditions may be obtained by obtaining as much data as possible from the same flight. This requirement arises from the expected difficulty of exactly reproducing flight conditions.

At the present time, the problem of providing a telemetering system meeting these requirements of light weight and a large number of channels has not been solved. The minimum number of channels that will provide any measure of satisfaction for aerodynamic and control system investigators is about one hundred. No systems are available which provide more than about thirty channels and are still within the limiting requirements of size and weight. Up to the present, attempts at reducing weight have been by reducing the size of components through the use of sub-miniature tubes and similar devices without any profoundly different approaches having been attempted.

CHAPTER III

PROJECTED METHOD OF SOLUTION

A study of the available telemetering systems indicates a common tendency toward duplication of circuitry and a lack of simplicity. The most obvious duplication is the use of a separate amplifier for each channel. It is immediately apparent that if a single amplifier for the whole system could be used, weight would be greatly reduced. In addition to the reduction of the number of components, much less power would be required for the fewer tubes used. A second inefficient use of tubes occurs in the commutation methods used. The two most common electronic methods[1] are the broken-ring trigger circuit[2] and the multivibrator chain.[3] In both these circuits, the tubes are productively active for only a very short fraction of the total time; the rest of the time they simply draw current and waste power. Power is also wasted in the continuous excitation of the measuring bridges.

1. The lack of success of the Vultee Radio Recorder eliminates the possibility of mechanical commutation for the sampling rates desired.

2. L. L. Rauch, "Electronic Commutation for Telemetering," Electronics, February 1947, V. 20, no. 2, p.114.

3. V. L. Heeren, C. H. Hoeppner, J. R. Kauke, S. Lichtman, P. R. Shifflett, "Telemetering from V-2 Rockets," Electronics, March 1947, V. 20, no. 3, p. 100.

With these thoughts in mind, the ideal system should embody a single amplifier, use a more efficient means of electronic commutation and excite the measuring bridges only when necessary. The possible use of a subcarrier system is eliminated by this last requirement since in this method of multiplexing the measuring bridges would have to be continuously excited and consequently the system would necessarily be less efficient than one employing time-sharing as the method of multiplexing. Simplicity is desirable since in general a simple circuit will be both lighter and more reliable than a complicated one.

With these as objects, the system indicated by the block diagram of Fig. 1 is proposed. The operation of the system is briefly as follows: The 25 kc oscillator and switching pulse generator produce a continuous 25 kc sine wave for excitation of the measuring bridges and a series of positive pulses at a repetition rate of 5 kc for switching purposes. The switching pulses go the input of a binary scaling circuit which, in conjunction with a resistance matrix, produces the gating pulses. These gating pulses are used to excite in turn the measuring bridges. The output of the measuring bridges goes to a common amplifier. The input to this amplifier is a series of blocks of 25 kc sine waves 5 cycles in duration, the amplitudes of the waves in each block being essentially the same and dependent on the unbalance in the measuring bridges. This sequence of blocks of 25 kc waves of dif-

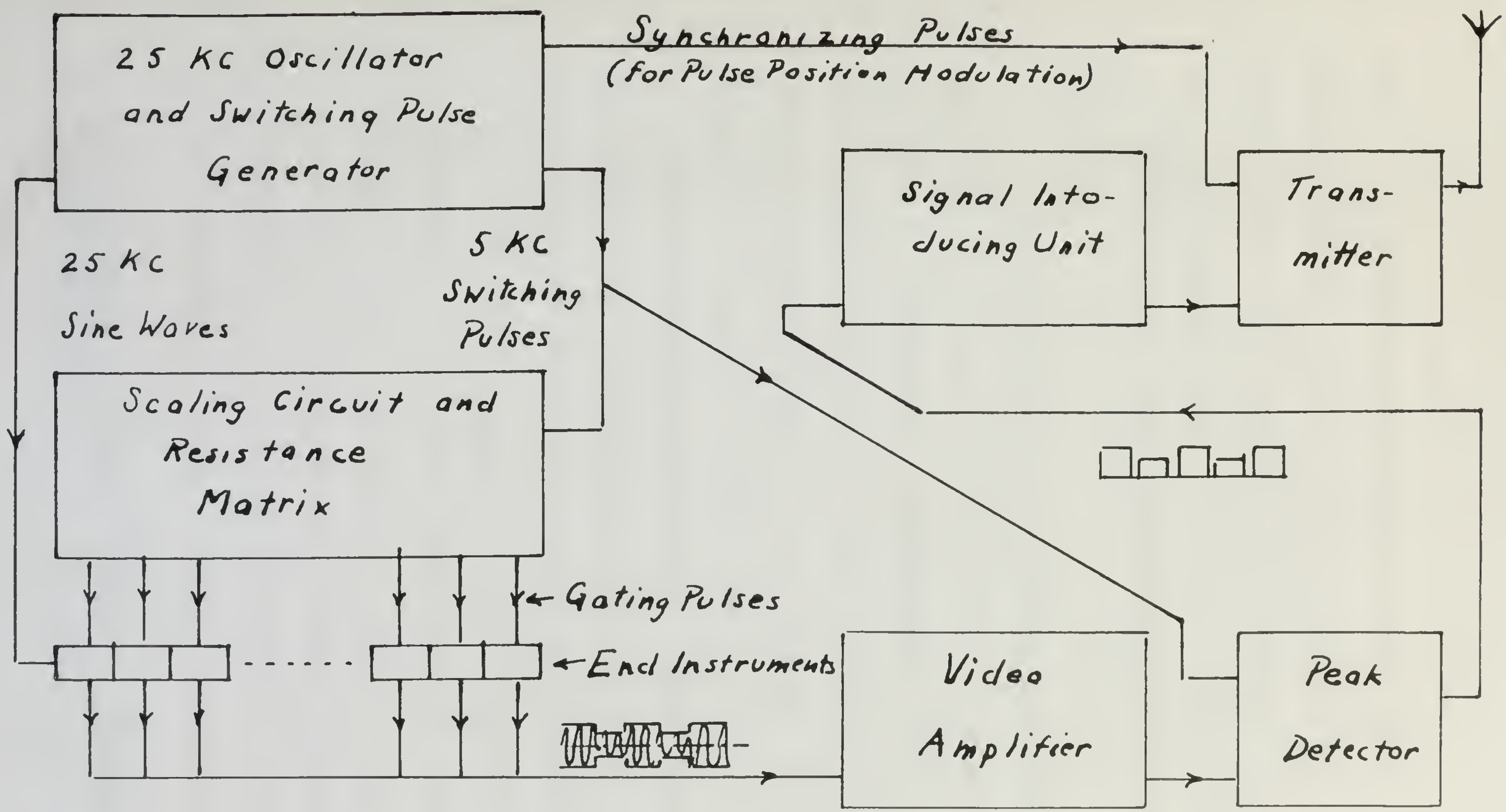


FIG.1. BLOCK DIAGRAM OF SYSTEM

ferent amplitudes is amplified and fed to a peak detector whose output is a sequence of positive pulses whose amplitudes are dependent upon the blocks of 25 kc input. The series of positive pulses is used to modulate the transmitted signal so as to indicate the intelligence obtained from the measuring bridges. This may be done by pulse position modulation, frequency modulation, or any convenient method.

For the purposes of this investigation only the parts which are a significant departure from conventional systems were constructed and investigated. These parts are: the scaling circuit-resistance matrix method of obtaining gates; the video amplifier and peak detector. The remaining parts of the proposed system offer no unusual problems and present no obvious possibilities of weight reduction. Since these parts are conventional communication circuits, it may be assumed that they are reasonably efficient.

The gate producing unit consists of a binary scaling circuit, its attendant amplifiers and drivers and a resistance matrix. (See Fig. 2 and Fig. 3) The scaling circuit used is an adaptation of one used by Grosdoff[1] and has the advantage of not requiring any diodes or crystals for its operation. It operates as a conventional binary

1. I. E. Grosdoff, "Electronic Counters," RCA Review, V. 17, p. 440, September 1946.

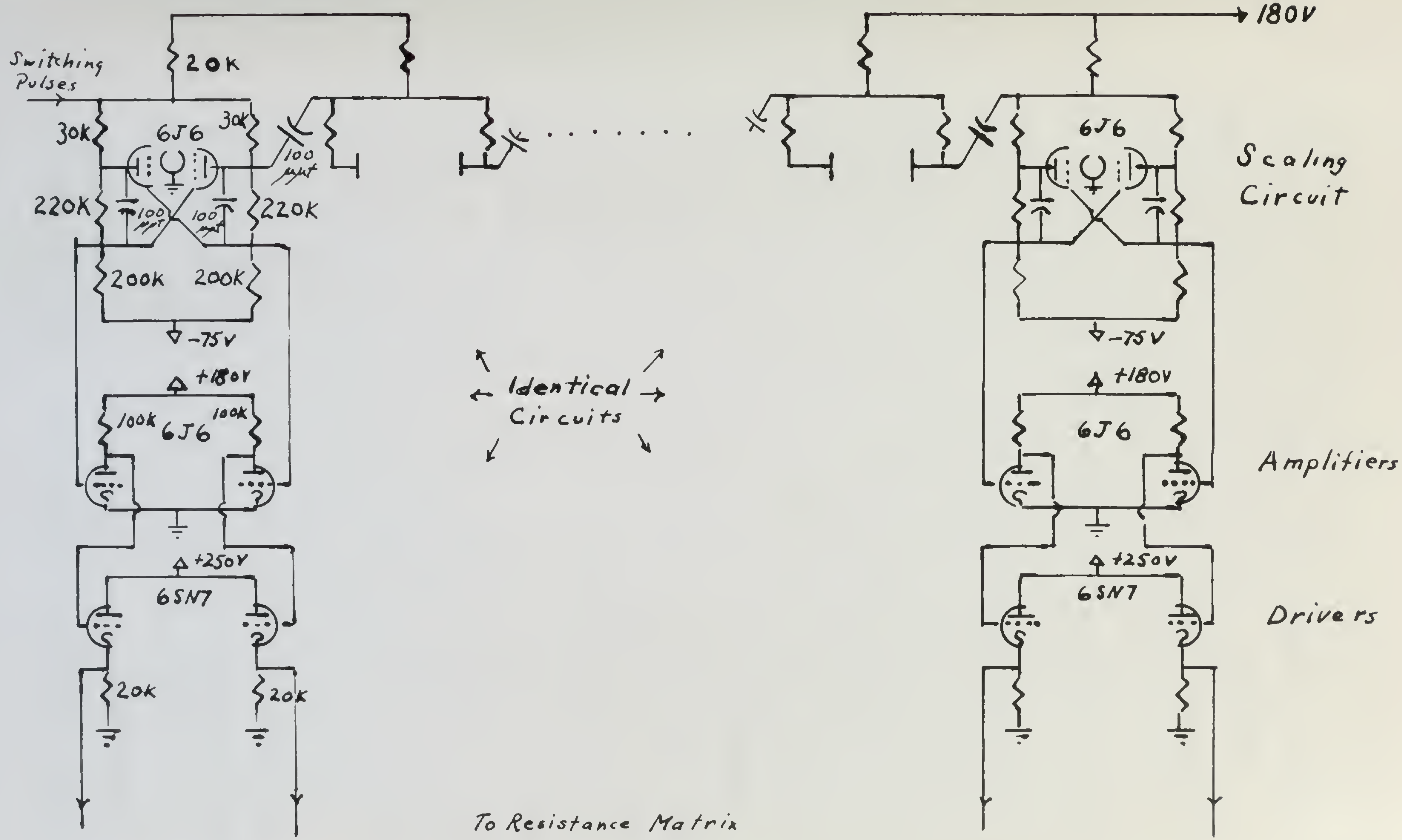


FIG. 2. SCALING CIRCUIT, AMPLIFIERS AND DRIVERS FOR MATRIX

scaling circuit with the first stage "flipping" on each input pulse and each subsequent stage "flipping" once for each two "flips" of the preceding stage. A six stage scaling circuit was used for this investigation resulting in the last stage "flipping" after 32 input pulses and in conjunction with the resistance matrix offering a possible 64 channels.

Originally it was hoped that the resistance matrix could be directly tied to the plates of the tubes in the scaling circuit. This unbalanced the scaling circuit to such an extent that operation was reliable for a plate voltage range of only two or three volts. For this reason the matrix was isolated from the scaling circuit by a direct coupled cathode follower for each plate. Without the amplifiers the gates available were only ten volts which were not large enough to operate the gating system in the most effective manner. For this reason the amplifiers were introduced. Their addition increased the size of the gates available to twenty volts, which was ample. The grids of the amplifiers and the grids of the scaling circuit units to which the amplifiers correspond are directly connected and the grids of the driver units are directly connected to theplates of the corresponding amplifiers. The driver stage was required in order that the gain in gate size in the amplifier would not be lost in driving the matrix. The addition of the driver stage also

scaling circuit with the first stage "flipping" on each input pulse and each subsequent stage "flipping" once for each two "flips" of the preceding stage. A six stage scaling circuit was used for this investigation resulting in the last stage "flipping" after 64 input pulses and in conjunction with the resistance matrix gating a possible 64 channels.

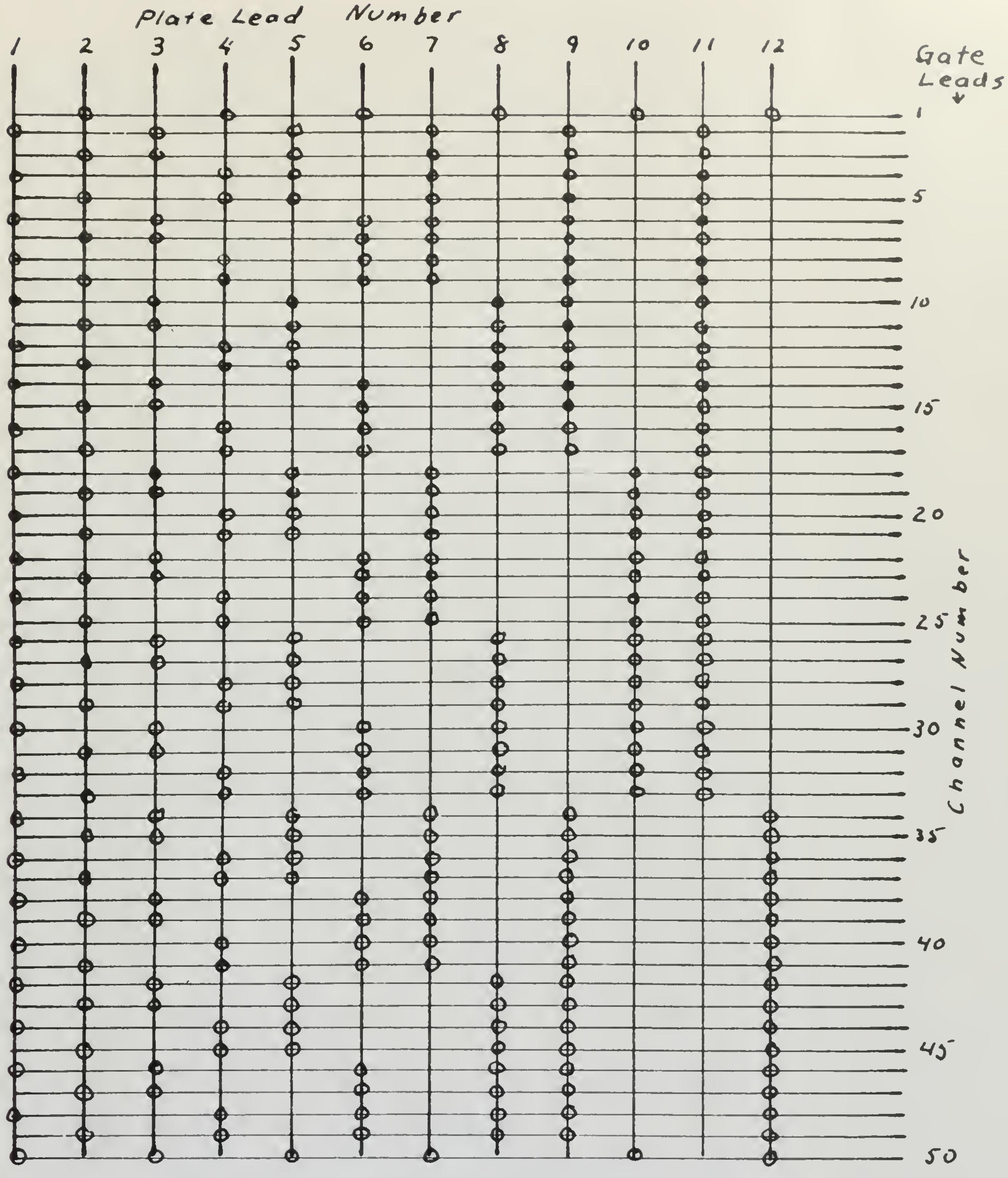
Originally it was hoped that the resistance matrix could be directly tied to the plates of the tubes in the scaling circuit. This unbalanced the scaling circuit to such an extent that operation was reliable for a plate voltage range of only two or three volts. For this reason the matrix was isolated from the scaling circuit by a direct coupled cathode follower for each plate. Without the amplifiers the gates available were only two volts which were not large enough to operate the gating system in the most effective manner. For this reason the amplifiers were introduced. Their addition increased the size of the gates available to twenty volts, which was ample. The grids of the amplifiers and the grids of the scaling circuit units to which the amplifiers correspond are directly connected and the grids of the driver units are directly connected to the plates of the corresponding amplifiers. The driver stage was required in order that the gain in gate size in the amplifier would not be lost in driving the matrix. The addition of the driver stage also

greatly improved the wave form of the matrix output, making the pulses much more uniform in size.

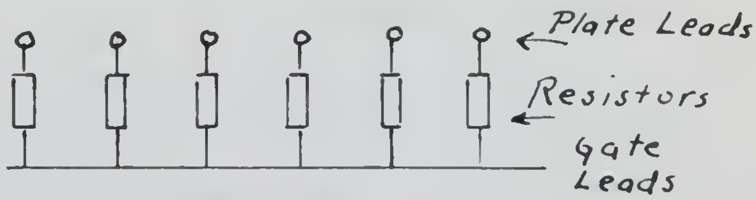
The negative bias supply is used instead of cathode bias in the scaling circuit since it results in a simpler circuit and a negative voltage is required for other parts of the system.

The completed scaling circuit with its amplifiers and drivers is very stable in operation irrespective of changes in plate supply voltage. Accurate scaling results when the plate supply voltage of the scaling circuit is changed from 90 to 200 volts and when the negative bias voltage is changed from 50 to 90 volts. This lack of dependence on a stable supply voltage is a great advantage in a telemetering system both from a standpoint of reliability and the weight saved by avoiding the use of complicated voltage stabilizing circuits.

The resistance matrix is very simple in operation in spite of the large number of resistors involved. Referring to Fig. 3, the leads labeled "Plate Leads" are actually the leads from the drivers. However, the voltages on these leads follow the plate voltages of the scaling circuit units, and by calling them plate leads the explanation of the operation is made much simpler.



Plan View



Side View

FIG. 3. RESISTANCE MATRIX

Each gate lead has six resistors on it, with each resistor going to a different plate lead. For example, the gate lead of channel No. 1 is connected by resistors to plates 2, 4, 6, 8, 10, and 12. When all these plates are nonconducting, the voltage on the gate lead will be at its maximum value, the nonconducting plate voltage. If any one of the plates is conducting, the voltage will be less. The next highest voltage occurs when only one of the plates is conducting. This voltage is less than the maximum value by $\frac{e_1 - e_2}{n}$, where e_1 is the nonconducting plate voltage, and e_2 the conducting plate voltage and n is the number of stages in the scaling circuit, in this case six. As additional plates are conducting, the voltage is reduced in steps of this same value, with the minimum value occurring when all are conducting. The value of these steps is decreased by the loading introduced by the other resistors to about half the calculated value in the actual circuit.

The different gates are obtained as a result of the scaling action of the circuit. The combination of the six nonconducting plates changes

with each input switching pulse, goes through a cycle and repeats after a number of input pulses which is equal to two raised to the n^{th} power where n is again the number of stages in the scaling circuit. The pattern of nonconducting plates may be seen in the plan view of the matrix in Fig. 3. The output of a typical gate lead in the matrix may be seen in Fig. 4.

The individual resistor size chose is one megohm. This value is a compromise between a high value, which would reduce the power required by the matrix, and a low value, which would lower the charging time constant of the matrix network resulting from the distributed capacity and the resistors. A higher resistor value undoubtedly can be used since some distortion of the matrix output can be tolerated and none at all resulted from charging lag with the one megohm resistors.

In order to insure identification of the channels, it was originally intended to force the scaling circuit to start with channel one before the regular switching sequence had been completed by impressing a negative voltage on the grids of the tubes which were to be nonconducting for the channel one gate. For this reason only 50 gate leads were in-

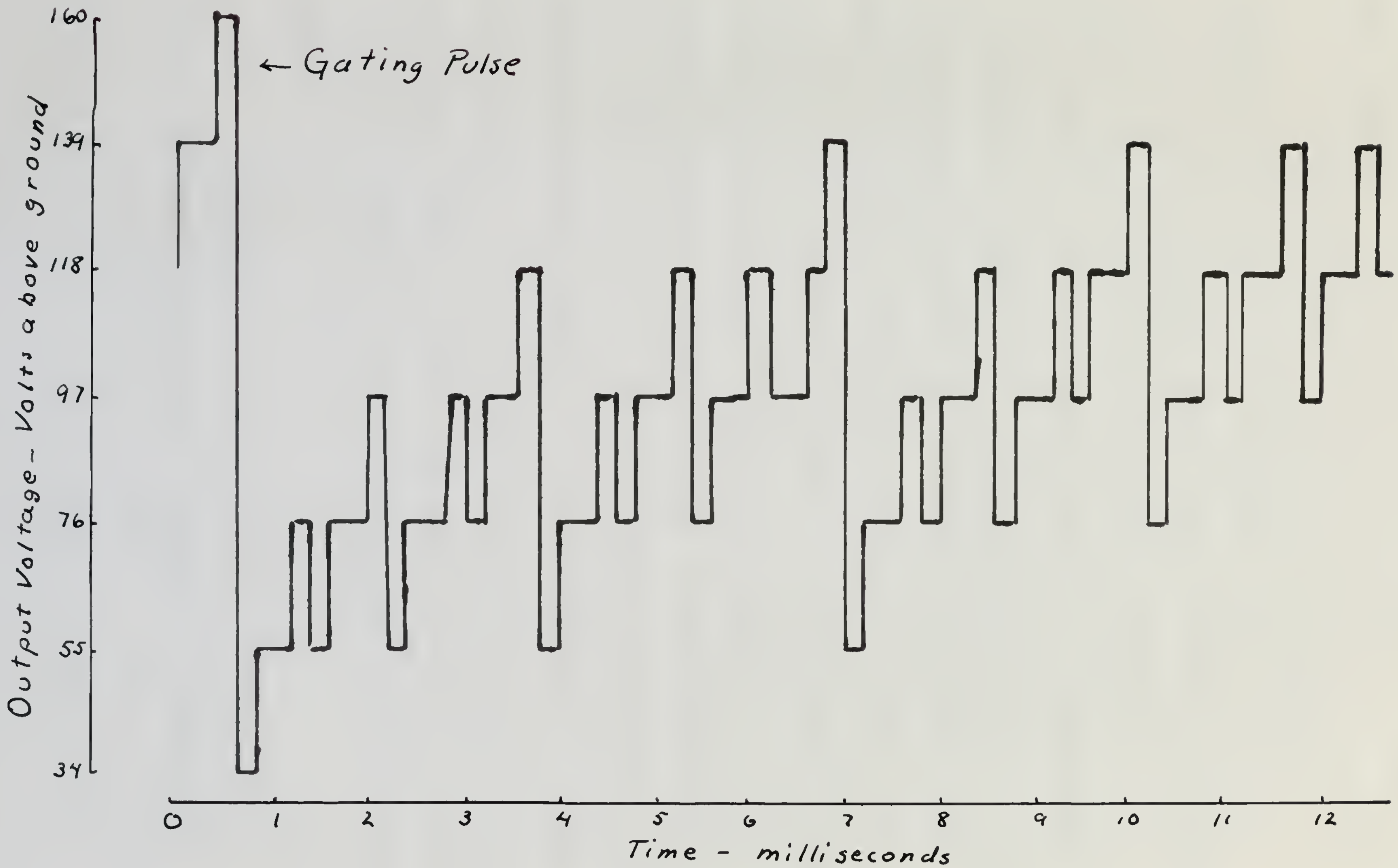


FIG.4. OUTPUT OF MATRIX (GATE LEAD, CHANNEL NO.1)

stalled. This scheme was abandoned in favor of the simpler system of leaving a sequence of channels blank. An example is channels 2, 25, 50 and 60. This method, in addition to being simpler than the original plan, is more positive in identifying the channels.

A variation of the matrix employs crystals instead of resistors as the elements. This method has the advantage of giving larger gates, the gates approaching $e_1 - e_2$, as previously identified. The preference for resistors in the matrix is a result of considerations of economy and reliability. The logical extension of the system considered is one giving about 120 channels. The number of crystals or resistors required is equal to the product of the number of channels and the number of stages in the scaling circuit. A gate-producing unit for 120 channels requires a scaling circuit of seven stages and consequently 840 crystals or resistors. This number greatly magnifies the difference in unit price between the crystals and resistors. If any one crystal were to break down half the channels would be lost. For these reasons, resistors appear superior in spite of the necessity of adding amplifiers.

As a means of reducing the power requirements of the system, it was decided to excite the measuring

bridges in succession rather than exciting all of them continuously. The individual power requirements of exciting a single bridge are easily met with even subminiature tubes while the power requirements of continuously exciting a hundred resistance strain-gauge bridges would require a good sized transmitting tube.

The first hope was that it would be possible to gate the excitation of the bridges by means of crystals. This was not possible since in order to keep the crystals biased to nonconduction between gates so much power was required from the matrix that the situation was entirely unreasonable.

The method used is shown in Fig. 5. Subminiature triodes are used instead of crystals. This results in an actual saving in weight since crystal gating requires the use of two transformers. Only one additional lead is necessary, one filament lead, since crystal gating also requires a bias supply. A further advantage of this system is that the excitation resulting is a normal sine wave, rather than a rectified sine wave as would be the case with crystal gating.

The operation of the gating system is as follows. Each switching triode is normally biased to cutoff and no current flows through its transformer. When a gating pulse arrives, the grid is driven positive and stays at very

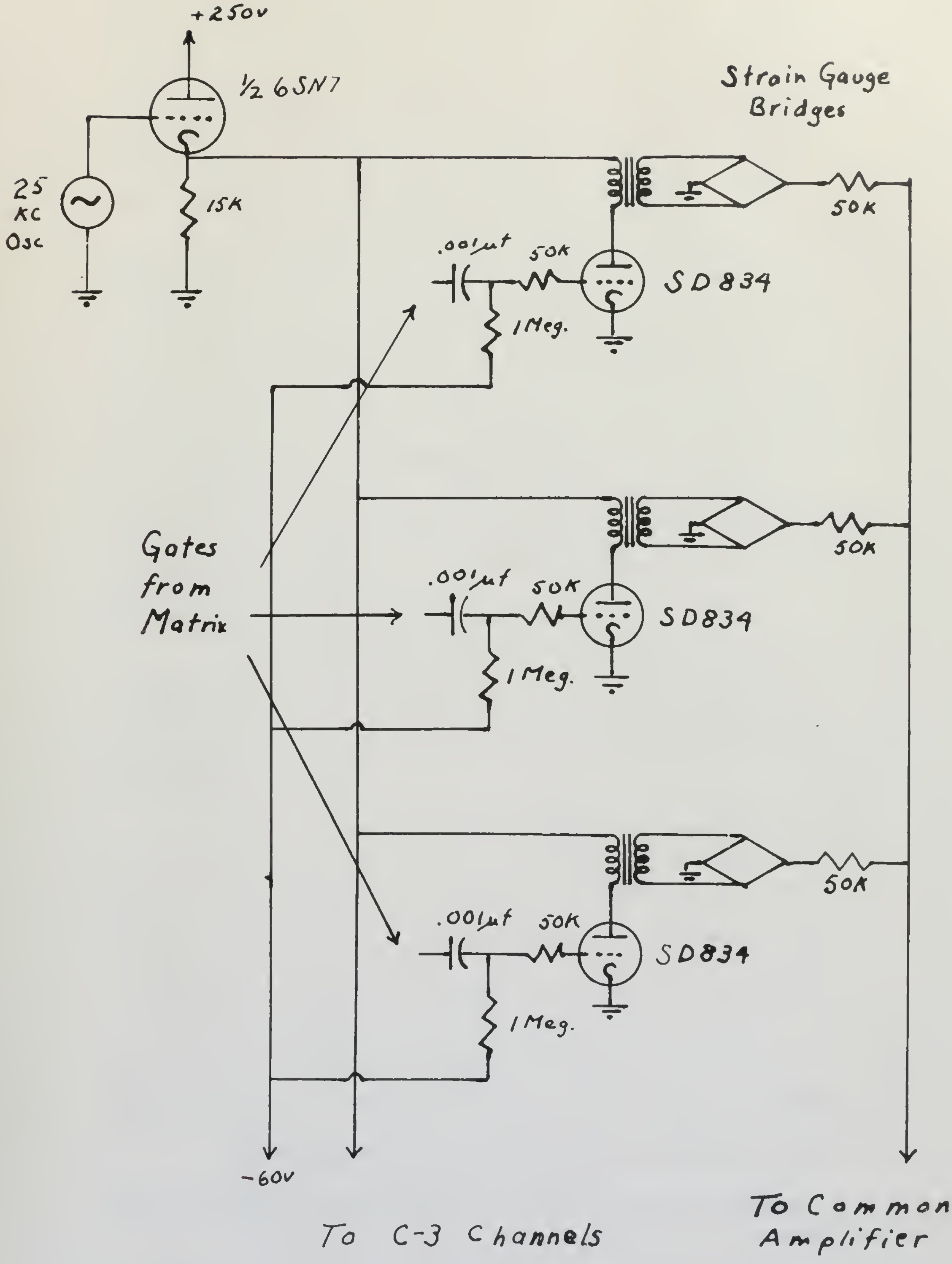


FIG.5. GATING SYSTEM

nearly cathode potential for the duration of the pulse because of the action of the grid-clipping resistor. The tube chosen, S D 834, has a plate resistance of about 3000 ohms that is very nearly constant for zero grid voltage despite changes of plate voltage. Consequently, the tube acts as an additional linear resistor during its conduction period. The low value of plate resistance permits a large fraction of the applied voltage to be developed across the transformer for excitation of the bridge. The action of these tubes was the factor which required the amplification of the gating pulses. A tube which required less cut-off voltage, thereby permitting the use of smaller gates, at the same time would have a larger plate resistance and, consequently, would reduce the available excitation voltage.

The resistors on the output of the bridges are for the purpose of reducing the effect of different states of balance in bridges other than the one excited. If 1000 ohm bridges and 50,000 ohm decoupling resistors are used, the maximum change possible in the input to the amplifier for a given bridge output is about 0.004%.

The transformers used in the experimental system were pulse transformers. It was hoped that these

would prove practical in the interests of lighter weight. Unfortunately, the use of pulse transformers limits the excitation voltage to about 4 volts while the use of bridge transformers would permit the use of 12 or 15 volts.

The video amplifier is conventional. (See Fig. 6) Rather high gain is necessary (a voltage gain of about 90 db is desirable) since the input to the amplifier is the output of the bridges reduced by a factor equal to the reciprocal of the number of channels. A tuned amplifier was originally proposed. This could not be used because of the build-up and decay times inherent in a system using resonant circuits.

The operation of the peak detector is easily followed in Fig. 6. A cathode coupled multivibrator is used to generate discharge pulses of about 50 micro-seconds in duration at the beginning of each gating pulse. These discharge pulses are applied to the grid of a discharge tube which discharges the 200 micro-micro-farad condenser in preparation for the next block of 25 kc waves from the succeeding channel. The increase in size of these d.c. output pulses of the peak detector was observed to vary directly with the amplitude of the 25 kc input to the amplifier (unbalance of a measuring bridge).

The parts of the system which were not constructed and were necessary for investigation were simulated with

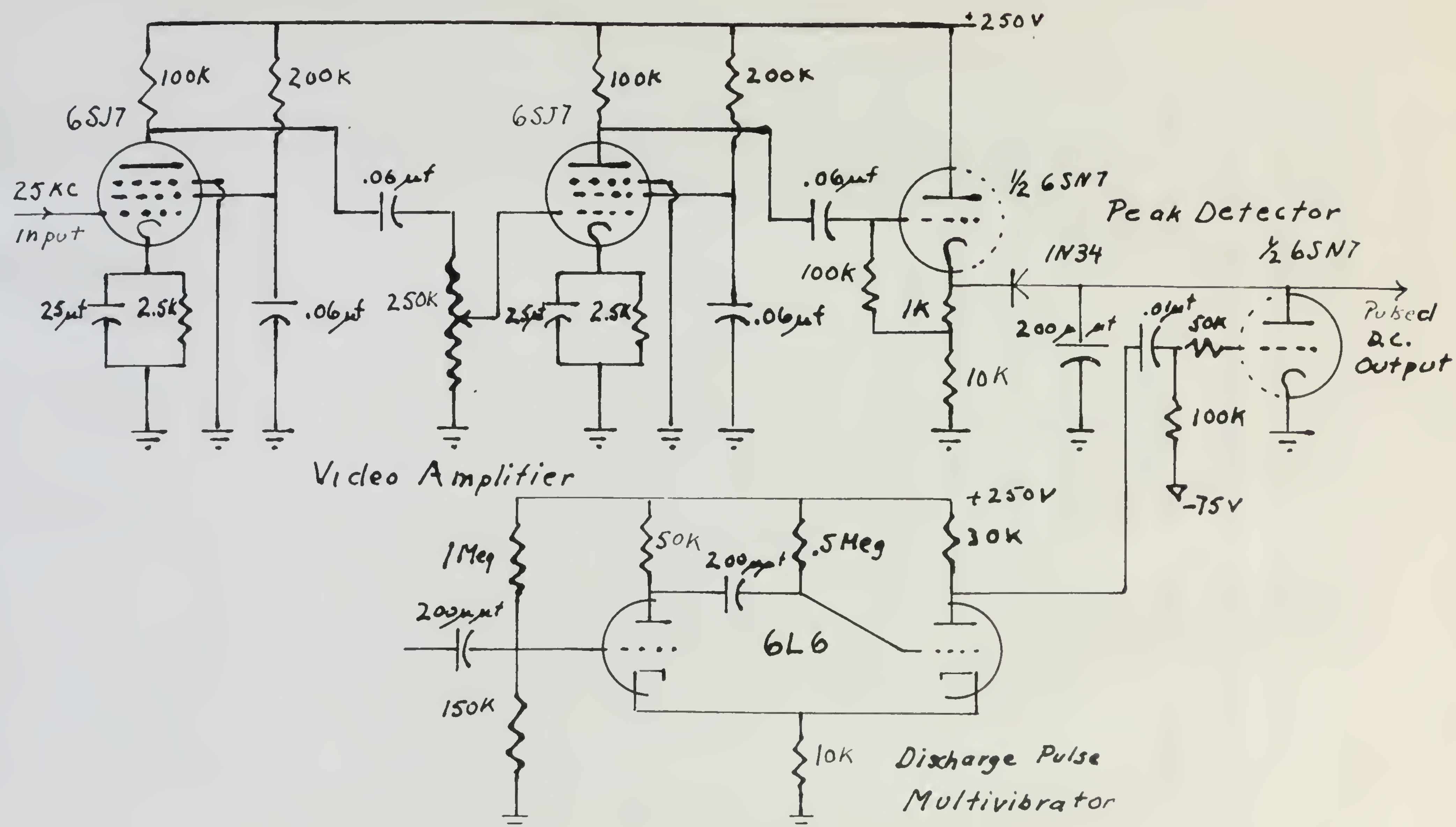


FIG. 6. VIDEO AMPLIFIER AND PEAK DETECTOR

regular laboratory equipment. The 25 kc oscillator was simulated with a Hewlett-Packard Model 200 D followed by one stage of triode amplification: the switching pulse generator with a Synchroscope Type P4E and the strain-gauge bridge with a resistance bridge having a potentiometer in shunt with a fixed resistor as the variable arm. Measurements were made with a Hewlett-Packard Vacuum Tube Voltmeter, Model 400 A for sine waves and a calibrated Dumont Model 208 Oscilloscope for pulses.

CHAPTER IV

CONCLUSIONS

The successful performance of the parts constructed indicates that a telemetering system embodying the principles that have been discussed could reasonably be expected to provide about a hundred channels and at the same time be lighter than any of the present systems providing about thirty channels.

In order to obtain twice as many gates as the scaling circuit-matrix that was constructed provides, it is necessary only to add three more pairs of triode units and approximately double the size of the matrix. The size of the gates available would be reduced by a factor of sixth-sevenths, which would not prevent operation. The additional end-instrument assemblies would be the only other parts necessary to double the number of channels of the system.

A comparison of the number of tubes required by the proposed system providing a hundred and twenty channels and the number of tubes required by a conventional system using a multivibrator chain method of gating,

continuous excitation of bridges and separate amplifiers for each channel indicates the savings possible.

Summary of Tubes Required for 120 Channels

Function	Proposed System	Conventional System
Gate Production	42	240
Amplifiers	3	240
Total	45	480

In addition to the reduction of the number of tubes there is an even greater reduction in the power required by the proposed system. The large number of resistors required by the matrix of the proposed system is a rather minor disadvantage since these resistors are much smaller than tubes and require practically no power. In any case, each additional tube of the conventional system could reasonably be assumed to require at least two resistors for its operation. There are 435 more tubes in the conventional system than in the proposed system, this number multiplied by two is 870 or thirty more than the number of resistors required in the matrix!

CHAPTER V

SUGGESTIONS FOR FUTURE WORK

The most apparent shortcoming of the proposed system is the basic inefficiency of using such a small fraction of the output of the measuring bridges as the amplifier input. (See Page 21.) For a large number of channels with the bridges near balance, the input to the amplifier approaches the noise level of the amplifier. A possible improvement is to use one stage of preamplification for a fraction of the total number of bridges and combine the outputs of the preamplifiers in a single amplifier. This, however, is an improvement and not a solution and is not very appealing since it returns to the situation of duplication of circuitry. A solution to this problem would greatly improve the proposed system.

No provision has been made in the system for automatic calibration while in flight. Some means of providing this function must be provided if any degree of accuracy is to be achieved. Investigation of this phase of the telemetering problem seems very much in order. Current systems seem to make excessive use of

mechanically moving parts to accomplish this function and it is recommended that investigation be in the direction of reducing or eliminating these moving parts.

The proposed system in its present state appears capable of providing a telemetering system with about one hundred and twenty channels. The construction and test of an actual telemetering system based on the principles discussed and using all possible means of sub-miniaturization seems worthwhile.

If the system is to be manufactured in any numbers, an investigation of the possibilities of "printing" the matrix network should be made. In this process, the wiring is printed on a steatite plate with a silver solution and the resistors in the form of a carbon resin mixture are sprayed onto the plate in their proper locations. The process has only been used for planar networks. However, the extension to the matrix should not be at all difficult since the wiring proper can be considered to lie in two parallel planes with the resistors in between. A possible method is to bore holes in the steatite in the proper places, fill the holes with a resistor paste and

1. Cledo Brunetti, A. S. Khouri, "Printed Electronic Circuits," Electronics, April 1946, V. 19, no. 4, p. 104.

paint the wiring on each side of the block. Probably the most convenient shape for the matrix is a cylinder. If it were this shape, the scaling circuit, amplifiers and drivers, the video amplifier, peak detector, and possibly the modulator could all be assembled in a cylindrical shape placed inside the cylindrically shaped matrix and the whole assembly "potted" in wax.

BIBLIOGRAPHY

1. R. Bureau, "Sondages de Pression et de Temperature par Radiotelegraphie," Comptes Rendues, June, 1929, V. 188, p. 1565.

2. Anon. Uber Radiosonde-Konstruktionen, Internationalen Meteorologischen Organization, March, 1937, Berlin.

3. E. Duckert, "Radiosonde Telefunken," Beitrage zur Physik der Freien Atmosphare, 1933, V. 20, p. 303.

4. O.S.R.D. Report, No. 1459, "Wurlitzer System for Telemetering Slow-Varying Flight Instruments."

5. H. D. Giffen, "Vultee Radio Recorder," Aeronautical Engineering Review, July, 1943, V. 2, no. 7, p. 9.

6. Instruction Book NDRC Telemetering System, Type 1 Model B, Raymond Rosen and Company, Philadelphia, Manufacturers.

7. Cledo Brunetti, A.S. Khouri, "Printed Electronic Circuits," Electronics, April, 1946, V. 19, no. 4, p. 104.

8. I. E. Grosdoff, "Electronic Counters," RCA Review, September, 1946, V. 17, p. 440.

9. L. L. Rauch, "Electronic Commutation for Telemetering," Electronics, February, 1947, V. 20, no. 2, p. 114.

10. V. L. Heere, C. H. Hoeppner, J. R. Kauke, S. Lichtman, P. R. Shifflett, "Telemetering from V-2 Rockets," Electronics, March, 1947, V. 20, no. 3, p. 100.

11. S. A. Forter, "The Development of Airborne Multi-Channel Telemetering," E. E. Seminar, M. I. T., 1947.